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THE ORIGIN OF THE EARTH

AND QUESTIONS OF ITS STRUCTURE AND COMPOSITION

B. Yu. LEVIN

Doctor of Physical and Mathematical Sciences

Less than 1% of the substance of the earth is accessible to direct study. For this reason correct ideas of the structure of the earth and the processes which take place in its interior can be formed only by way of comprehensive utilization of all available data, physical, geophysical, geochemical, geological, astronomical, and cosmogonic. The theory of the origin of the earth is based not only on information about our planet, but also on a large quantity of data on the solar system and the individual bodies of which it is made up. Drawing upon the cosmogonic theory substantially increases the number of supporting facts and, in particular, permits valid use to be made of comparative analysis of the structure and development of the earth and the planets related to it, as well as of the numerous data on the meteorites. Planetary cosmogony plays an important, and at times even decisive, part in study of such questions as the composition of the earth and the nature of the earth's dense core, the heterogeneity of the interior of the earth and movement of the poles, the thermal history of the earth and the process of fusion of the earth's crust.

At the beginning of the 1940's, Academician O.Yu. Shmidt arrived at the conclusion that the planets were formed by accumulation of cold solids and particles. Of particularly great significance to geophysics was O. Yu. Shmidt's conclusion that the earth was initially cold and only later was heated as the result of accumulation of radiogenic heat.

The majority of investigators throughout the world (G. Yuri /H. Urey?/, F. Hoyle, T. Gold, and others) have by now arrived at the same fundamental conclusions.

The aggregate of the factual data on which the cosmogonic theory is based and which are to explain it was graphically termed the "boundary conditions" of the problem by G. Yuri. The most important "boundary conditions" include both the mechanical laws governing the movement of the planets and reliable data on the structure and composition of all the bodies of the solar system. Amid the evidence confirming the origination of the earth by the accumulation of cold bodies, special importance attaches to the deficit within the earth of elements which form volatile compounds and of heavy inert gases, with simultaneous retention both of non-volatile elements and of elements of medium volatility (mercury, cadmium, zinc).

In explanation of the distribution of angular momentum between the sun and the planets, O. Yu. Shmidt advanced the hypothesis of capture of matter by the sun for construction of the planets. The capture of a swarm of bodies was first assumed, and then, after it had been ascertained that the relatively large bodies from which the planets were directly formed appeared in the environs of the sun, the assumption was advanced of capture of a protoplanetary cloud of gas and dust[1].

1. In O. Yu. Shmidt's first articles on cosmogony, the hypothesis of capture of protoplanetary matter by the sun was incorrectly considered to be the basis for explanation of the formation of the planets. This error was rectified in the 50's. It is emphasized in "Four Lectures On The Theory Of The Origin Of The Earth" that "the theory of formation of the planets from a cloud of gas and dust and explanation of all the fundamental features of the solar system are logically independent of the hypothesis concerning the origin of this cloud." Nevertheless, objections to the hypothesis of capture of protoplanetary matter continue to be represented at times as objections to O. Yu. Shmidt's theory.

F. Hoyle recently gave concrete expression for the first time to the hypothesis of joint formation of the sun and the protoplanetary cloud. He demonstrated that the problem of moments can be solved on the basis of the idea of magnetic cohesion between the still contracting sun and the matter separated from it. It is true that the mechanism of transfer of momentum to the outer portions of the cloud remains vague.

Both in the case of cloud capture and in the case of formation of the cloud together with the sun, the duration of the process was probably relatively great. Hence further evolution of the cloud, the first stages of which were heavily dependent on the manner of its origination, must have begun even before completion of the process. In the present state of our knowledge it is necessary to consider the evolution of a cloud which has already formed. This makes it possible conditionally to distinguish two stages: the first, gathering of the dust component of the cloud into a flat disk and its decomposition into clusters subsequently united in intermediate bodies of the size of asteroids, and the second, accumulation of the planets from the swarm of asteroid bodies and fragments of the latter. The physical and chemical processes, condensation and evaporation of solid particles, proceeded with particular intensity during the first stage, but also continued during the second. They were closely related to the mechanical evolution, accumulation of larger bodies bringing about change in the transparency of the spaces, and at the same time in the temperature conditions. The physical and chemical conditions also continued in the interior of the asteroid bodies, particularly as a result of their radioactive heating.

Study of the physical and chemical aspect of evolution of the protoplanetary cloud is still in its infancy. The general difference in temperature conditions in the internal and external zones of the cloud explains the existence both of the small but dense planets of the earth group, consisting of non-volatile substances, and of the giant planets of low density containing volatile compounds and elements, including hydrogen. But the composition of each planet, and the earth in particular, is an integral effect of the temperature conditions in the "alimentation zone" of the given planet, which changed in the course of the accumulation of the latter, and what is more, differed somewhat on the internal and external boundaries of this zone.

Precise solution of the mechanical problem of accumulation of the planets calls for the development of new research methods intermediate between statistical celestial mechanics and statistical physics. What is involved is study of the kinematics of the processes in a revolving system of gravitating bodies of variable mass, in which inelastic collisions occur which sometimes lead to fractionation and sometimes to unification of the bodies. At the present time the mechanical evolution must be studied in approximation. Doing this does not, however, prevent the making of a sufficiently reliable evaluation, for example, of the tempo and duration of formation of the earth.

The question of the composition of the dense core of the earth, which comprises about one-third of the earth's mass, has remained vague up to the present time. After predominance of the hypothesis of an iron core for a century and a half, Ramsey's hypothesis, which ascribes formation of the core to phase transformation of silicates into a dense metallic state under the influence of high pressure, made its appearance several years ago.

The iron core hypothesis arose on the basis of the analogy between the presumed "molten" initial stage of the earth's existence and the metallurgical furnace. It later came to be based on analogy between the earth and a hypothetical planet the decomposition of which allegedly gave rise to meteorites.

If we proceed on the basis of the hypothesis of an iron core for the earth and compare the average densities of the planets of the earth group (see Table), the conclusion is inescapable that their content of metallic iron, and of iron in general, differs. Thus, in the earth and Venus the iron content should under this hypothesis amount to about 45%, but should be much less in Mars, and especially in the moon.

Planet	Mass	Average density, g/cm^3
Mercury	0.0543	4.5 — 5.5
Venus	0.814	5.0 $\pm$ 0.1
Earth	1.00	5.52
Mars	0.107	4.0 $\pm$ 0.1
Moon	0.01226	3.33

The attempts at cosmogonic explanation of these differences made in recent years by G. Yuri (1950-1960) and Ch. Ringwood (1959) have not proved successful. Insuperable difficulties persist even within the framework of the highly artificial schemes proposed by these authors.

During the era of predominance of the concepts of a "molten" initial state of the earth, formation of the iron core was assigned to this stage. Later, when the opinion that the earth was formed as a cold body arose, formation of the iron core began to be ascribed to gravitational differentiation which started after radioactive heating and softening of the earth's interior. However, the ductility of the interior is so great that even the enormous iron inclusions (tens and hundreds of meters in diameter) would have had to "sink" at a negligibly small speed and would not have been able to descend toward the center and form a core, even during the billions of years of the earth's existence.

It has recently been ascertained by experiments on the impact compression of iron that the density of the core is too great at the pressures prevailing in it. The calculations, in which an attempt was made to lower the density by increasing the temperature, showed that agreement with the actual density is achieved only at an unrealistically high core temperature, if we assume, for example, the presence in the core of an admixture of silicon or magnesium, but this would mean rejection of the analogy with the iron meteorites.

The merit of Ramsey's hypothesis, which determined its acceptance by a number of geophysicists, is the conclusion regarding the approximately identical composition of the planets of the earth group[2] and the moon; because of it the problem of gravitational differentiation does not arise.

Ramsey himself gave no calculations of the phase transformations in the silicates or even in the oxides, merely referring to similar calculations for hydrogen. A theoretical calculation for magnesium oxide made recently at the O. Yu. Shmidt Earth Physics Institute, and experiments on the impact compression of dunite yielded no phase transformation at a pressure of 1.4 million atm (the pressure at the boundary of the

2. Mercury, the average density of which is too great (see Table), is apparently the only exception. This may be ascribed to the fact that Mercury, being the planet nearest the sun, was formed from particles more greatly heated by the sun or was even condensed under conditions of increased temperature. Elucidation of this question is one of the problems of investigation of the physical and chemical evolution of the protoplanetary cloud.

earth's core). This naturally raises doubts as to the correctness of Ramsey's hypothesis. However, the author of this paper is not inclined to consider these results as definitive. After comparing the serious difficulties encountered by the iron core hypothesis with the merits of Ramsey's hypothesis, he remains an advocate of the latter.

From the time of P. N. Chirvinskiy's first paper (1919) to this day, the analogies with the composition of meteorites have served as the basis for all works dealing with the composition and structure of the earth's mantle (shell). Referring to the general laws of cosmic chemistry, some investigators have used these analogies even when hyperbolic velocities were ascribed to meteorites, i.e., when they were considered as bodies of interstellar origin.

The membership of meteorites in the solar system has now been firmly established. This permits drawing with good cause on data on the composition of meteorites in order to judge the composition of the earth.

If the iron core hypothesis, which involves the inference of a different iron content in the planets of the earth group, is adopted, it is natural to assume that the planets will be found to differ one from the other, and from the meteorites, in the content of other elements.

If, on the other hand, Ramsey's hypothesis is adopted, as seems proper to us, a much greater similarity is to be expected between the composition of the earth and that of the meteorites, both the mantle and the earth as a whole being involved in this case. The average chemical (but not mineralogical) composition of the earth as a whole may in the first approximation be considered to coincide with the average composition of meteoritic matter. The fact that the density of the moon is near the average density of meteoritic matter serves as confirmation of the correctness of this assumption.

Of course, the composition of the meteorites can characterize the earth's content only of elements which form only non-volatile compounds at temperatures of the order of 0°C. One must be extremely cautious in dealing, for example, with oxygen, which forms both non-volatile and volatile compounds at these temperatures. But for the elements which form only difficultly fusible compounds there are indications that the composition of the mantle, and possible all the earth, differs from the composition of the meteorites. Such differences are natural. The asteroids, of which the meteorites are fragments, were formed farther from the sun than was earth, i.e., under different temperature conditions. The asteroids are found at the point of junction of the zone of earth planets and the zone of giant planets. During the age of their formation, when interplanetary space was still filled with dispersed matter and hence opaque, they belonged to the cold zone. The question of how much colder it was then than now in the zone of formation of the earth and of how temperatures in the region of the earth differed from those in the region of the asteroids, has not thus far been studied.

It must not be forgotten that little is known of the average composition of meteoritic matter. The trouble does not at all lie in the small number or unreliability of the analyses of uncommon elements (radioactive ones, for example). We are completely ignorant of the composition and quantity of the friable bodies completely destroyed in the atmosphere and thus not reaching us. We cannot even properly account for the differing destruction of iron and stone meteorites in the atmosphere. For this reason some authors refrain from making evaluations of the average composition and adopt chondrites, meteorites of the commonest type, as specimens of difficultly fusible protoplanetary matter. Quite recently, however, indications have begun to accumulate that it is not the "ordinary" chondrites but a rare variety of them, the carbonaceous chondrites, which best characterize the composition of this matter. Further research must clarify the extent to which the carbonaceous chondrites may at the same time be considered to be the best specimen of terrestrial matter.

Despite vagueness and difficulties, the concept of a meteoritic initial composition of the shell has proved to be fruitful in several respects. Above all, it has permitted quantitative explanation of the heat flow coming from the interior of the earth toward the surface. Ever newer confirmations are accumulating of the fact that meteoritic matter (or matter similar to it) is a suitable initial substance for fusion of the earth's crust.

Formation of the earth by accumulation of asteroid bodies and fragments of the latter moving in the environs of its orbit permits the assumption of a distribution of the bodies and fragments such that a few large bodies brought to earth more matter than did the countless small particles. The earth grew chiefly as the result of the falling to it of large bodies up to several hundred kilometers in diameter.

Had these large bodies been of absolutely identical composition, the resulting interior of the earth would be just as homogeneous as in the case of its growth out of small particles. However, the differences in the content of nickel and certain other elements in the iron meteorites indicate that there were also differences in the composition of their "parent" bodies, the asteroids.

Since differences exist in composition within the limits of the contemporary asteroid ring, it may be assumed that the asteroid bodies formed within the limits of the earth's "alimentation zone" also had no rigorously uniform composition, and together with this, slightly differing density. For this reason the falling of large bodies to earth naturally caused a slight heterogeneity in its interior.

Later, in the course of radioactive heating and partial fusion of the interior, the certain heterogeneity of its composition must have led to uneven fusion of the matter of the earth's crust. This possibly is also the reason for the existence of its continental and oceanic portions.

Any displacement of large masses means deformation of the earth's ellipsoid of inertia and must cause shifting of the axis of rotation relative to the earth, i.e., movement of the poles. The heterogeneity of the earth's interior may be the reason for movement of the poles, owing both to the irregularity of the process of fusion of the earth's crust and to shifting of the interior masses, subsidence of the heavy regions and floating up of the light ones, which must have begun after softening of the interior as it became heated. For regions hundreds of kilometers in diameter, differences in density even smaller than 0.1 g/cm^3 are sufficient for beginning of such movement.

The progress of many important processes taking place in the earth's interior, in particular the progress of fusion of the earth's crust from the matter of the mantle, is determined by the thermal history of the earth. During the era of predominance of the concepts of an incandescent initial state of the earth, it was held that the fundamental gravitational (and together with this chemical) differentiation of telluric matter occurred during the "molten" stage, while the subsequent processes, including the contemporary ones, are secondary in nature. Contemporary data on the cold initial state of the earth and on its protracted heating by radiogenic heat led to the idea of gradual differentiation of the earth's interior, a gradual formation of the earth's crust which is still continuing.

In all calculations of the thermal history of the initially cold earth, the latter's average content of radioactive elements is assumed to be the same as in the meteorites. The value of the content of these elements in meteorites has been appreciably reduced in recent years, owing to the application of improved methods of analysis. While earlier comparison of heat release in the earth with the flow coming from the interior toward the surface and lost in space led to the conclusion of continuing accumulation of heat in the earth, it follows from later data that we are somewhere in the region of a gently sloping thermal peak of the plutonic parts of the earth. According to earlier data, almost throughout the mantle the contemporary temperature should have exceeded the fusion temperature, and for this reason it was necessary to assume an amorphous, but solid, state of matter. According to later data, the fusion temperature is reached only in a certain thick layer located at a depth of several hundred kilometers. This agrees with the conclusions of seismology and geochemistry that the earth's crust was not fused from all the mantle, but only from its upper part.

Even with uniform distribution of radioactive sources of heat over the earth, an already cooling outer zone and a central region continuing to heat up must have coexisted in the earth in certain stages of evolution. Evacuation of the radioactive elements from the upper part of the mantle into the crust in the course of formation of the latter greatly complicates this picture. It is possible that the continuing formation of the crust leads to rise in temperature in the region of the Mohorovicic boundary, with simultaneous decrease in the temperature of the upper portion of the mantle and continued heating of the lower portion of the mantle and the core.

Only ten years ago, when the content of radioactive elements in meteorites was assumed to be ten times greater than it is now, it was not clear whether the content was sufficient to explain the contemporary incandescent state of the earth's interior. Now we not only are satisfied with a content of these elements which is many times smaller, but in addition are striving to establish it with an accuracy greater than can be afforded by analyses of meteorites. Unfortunately, we do not have sufficient data on the total heat flow irradiated by the earth into space, and, moreover, we know little about the heating capacity of the incandescent matter of the earth's interior and the laws of redistribution of radioactive elements in the course of formation of the earth's crust. For this reason we cannot determine the average content of radioactive elements with greater precision by considering the earth alone. But we may rely on achieving success by simultaneously considering the thermal history of the moon (as well as Mars).

In the earth, owing to its great mass and the enormous pressure in its interior, the fusion temperature rises appreciably with increasing depth. For this reason the fusion temperature is not reached in the lower part of the mantle. The pressure in the moon is slight, and fusion there (partial or total) must have ensued almost immediately in the broad central region. This led to a course of differentiation of the interior which differed from that of earth. Owing to their characteristics of being concentrated in the first melts, the radioactive elements must largely have been evacuated from the entire volume of the moon toward the surface. This, together with reduction in the supply of these elements due to their decay, long ago led to transition from heating to cooling of the moon.

In other respects the development of the interior of the moon conformed to the contemporary concepts of development of the earth's interior. The development was not accompanied by any unusual processes which might have led to endogenic formation of such peculiar relief forms and the lunar craters. The latter are neither volcanic cones nor calderas. The lunar craters are of exogenic origin connected with the bombardment of the moon by the bodies which formed it. The radioactive element content of the moon must have been such as to ensure partial fusion of its interior while bombardment of its surface by enormous bodies continued. Formation of the lunar lava "seas" and lava-inundated cirques occurred during the concluding stages of this bombardment.

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The questions under discussion of study of the composition of the core and mantle of the earth, the heterogeneity of its interior, and its thermal history do not exhaust all the problems in the solution of which the theory of the earth's origin and planetary cosmogony in general play an important part. We shall give two examples. The unity of composition of the earth and moon is naturally accompanied by a similarity in the rheological properties of their matter. The disequilibrium of the shape of the moon, which has been preserved for billions of years, shows that lunar matter, like that of the earth, possesses a creep threshold. The oblate nature of the moon's dynamic shape is apparently to be ascribed to its solidification in a state of free rotation which was subsequently retarded as a result of dissipation of energy in the solid tides, i.e., due to the non-ideal elasticity of its matter. A similar phenomenon has now been discovered in telluric substance in study of the solid tides of the earth, but quantitative study of the phenomenon is complicated by the existence on the earth of marine tides as well. There are no such tides on the moon, and for this reason it is to be hoped that study of the history of rotation of the moon will greatly assist "telluric" research.

The second example pertains to another region. It may at first glance appear surprising that the origination of the earth's hydrosphere and atmosphere is possibly closely related to the origination of the gigantic cloud of comets which, as was established by Ya. Oort (1950), now surrounds the solar system. The ice cores of the comets making up this cloud were ejected from the zone of formation of the giant planets during the concluding stage of this process. Some of them traversed the interior zone of the planetary system and sometimes collided with the nascent earth, bringing water and other volatile substances, including hydrocarbons, to it.

Future research will show whether this was the principal means whereby the earth acquired volatile substances, or whether the latter entered its composition through the asteroid bodies of the earth's own "alimentation zone," which were similar to the carbonaceous chondrites.

In keeping with the questions discussed above, three basic directions may now be indicated for further research into planetary cosmogony, ones which are of the greatest importance for study of the earth: study of the physical and chemical evolution of planetary matter; study of the process of accumulation of planets; comparative study of the planets of the earth group and the moon.

Research in the first direction must cover a wide range of questions concerning primary condensation of solid particles in the protoplanetary cloud (what with the different hypotheses as to its origin), clarification of the role of volatile substances in the zone of the planets of the earth group, and losses of volatile substances by asteroid bodies and accumulating planets due to change in external temperature conditions and internal heating. The questions of the formation and composition of the bodies of the cold zone (giant planets, cores of comets) must also be studied.

The principal astronomical results of this research will be establishment of the dependence of the composition of planets on their distance from the sun, clarification of the origin of meteorites of various types, and determination of the structure of comet cores and meteoric particles of comet origin. The greatest interest to geophysics will be presented by study of the difference between the composition of the earth and that of meteorites and evaluation of the extent of heterogeneity of the earth's interior, evaluation of the iron content in the earth for the purpose of clarification of the nature of the earth's core, and, lastly, study of the origin of the original atmosphere and hydrosphere of the earth and laying of a cosmogonic foundation for theories of the origin of petroleum and life on the earth.

Research in the second direction must be aimed at study of the process of formation of asteroid bodies and at accounting for the phenomena of fractionation and gradual growth of velocity dispersion upon the subsequent accumulation of planets. Both the elaboration of new precise research methods and the use of the approximate methods of physical statistics will be required for this purpose.

It is to be assumed that this research will make it possible to ascertain the duration of formation of the individual planets and estimate their initial temperature, to provide a correct development of the "law of planetary distances" which accounts for the connection between this law and the masses of planets, and to study the origin of the satellites of planets. Results of great importance to geophysics will be precise determination of the duration of formation of the earth and the initial distribution of temperature along the radius, evaluation of the quantity of the ice cores of comets which have fallen to the earth, and study of the rise of the axial rotation of the earth and its subsequent history.

Research in the third direction must cover comparative study of the thermal history and development of the interiors of the planets of the earth group and of the moon, the history and composition of their atmospheres, and, lastly, thorough analysis of their average densities. On the one hand this research will assist astronomical observers in ascertaining the physical conditions on the surface of planets, and on the other will permit precise determination of the content of radioactive elements in the earth and trace its thermal history, which determines the course of fusion of the crust from the mantle, and determine more accurately the distribution of density along the radius of the earth and reveal the role of differentiation of telluric matter.

Development of the theory of the origin of the earth, which is an inseparable part of planetary cosmogony as a whole, represents one of the most promising methods of solving many geophysical problems.